The Total Hemispherical Emittance of Polyimide Films for Space Use in the Temperature Range 173 K to 700 K [1]

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ABSTRACT

Thermal control materials covering a spacecraft for Mercury orbiter mission are required to have stability against the severe thermal environment. This paper describes the temperature dependence of the total hemispherical emittance ε_h in the temperature range from 173 to 700 K for three types of thermal control material, which is based upon a thin polyimide film coated with aluminum on the back surface. The results obtained from the measurements are compared with the calculated ones from optical constants. The principle of the present measurement is based on the steady-state calorimetric method and ε_h is obtained by measuring the equilibrium temperature of a sample corresponding to different heat input given to a heater attached to the sample. On the other hand, the present calculation method is performed by using data for the optical constants of polyimide films and vapor-deposited metal in the wavelength region from 0.25 to 100μm. These results agree well each other on the whole. It has been observed that the temperature dependence of ε_h is remarkable and the values have a maximum around 410 K.

KEY WORDS: Mercury orbiter mission; optical constants; polyimide film; steady-state calorimetric method; thermal control materials; total hemispherical emittance.

1. INTRODUCTION

There are so many thermal engineering problems on a scientific exploration mission of the Mercury, the most inner and hottest planet of the Solar System. The Mercury orbiter mission spacecraft receives an intense illumination ten times larger than near the Earth and, at the same time, is exposed to the energy radiated from the Mercury, whose surface temperature is over 700 K. The harsh thermal environment of the Mercury, compared to that of the Earth, is shown in Table I [1,2]. The distance between the Sun and the Mercury varies from 0.306AU (Astronomical Unit) to 0.47AU, so the maximum solar flux intensity around the Mercury at the perihelion is about 10.6 times larger than one around the Earth. Even at the aphelion, the solar intensity reaches to 4.6 times larger. And owing to the Mercury's low albedo, the maximum infrared intensity from the Mercury reaches to about 13470 $W \cdot m^{-2}$ at the perihelion, which is over 50 times larger than an orbit around the Earth. Therefore, thermal control materials covering a spacecraft for the Mercury exploration are required to have stability against the severe thermal environment as well as widely varying heat flux during the cruising orbit. This paper describes the temperature dependence of the total hemispherical emittance ε_h of three types of thermal control material based upon polyimide films for space use in the temperature range from 173 to 700 K by means of experimental measurements based on the steady-state calorimetric method and calculations from optical constants.

2. THERMAL CONTROL MATERIALS

In general, multi-layer insulation (MLI), which consists of many sheets of thermal control films, is used on various spacecraft surfaces as the main passive part of the thermal control. Thermal control films are usually thin polymer films with vapor-deposited metal on the back surface [3]. It is well known that polyimide films are superior in long-term heat resistance, chemical resistance, irradiation resistance etc.

among polymer films. The polyimide film Kapton-H™, which produced from pyromelitic dianhydride and 4,4'-diaminodiphenyl ether (DADE), and UPILEX-R™ (UBE industries, Ltd.), which produced from 3,3', 4,4'-biphenyl tetracarboxylic acid dianhydride (s-BPDA) and DADE, have been loaded on a lot of spacecraft [3,4]. In recent years, the polyimide film UPILEX-S™ (UBE industries, Ltd.), which generated from s-BPDA and p-phenylene diamine, has been developed. UPILEX-S film is superior in long-term heat resistance, compared with Kapton-H and UPILEX-R. Chemical structures of polyimide films are shown in Fig.1. The long-term thermal life of polymer films is usually determined by the Arrhenius plots of a half-life of tensile strength. The temperature (T_{20000}) corresponding to the half-life extrapolated to 20000 hours of tensile strength in the Arrhenius plots, and the glass transition temperature (T_g) are shown in Table II [5,6].

3. MEASUREMENTS

3.1. Principle of the measurement [7]

The principle of the present measurement is based on the steady-state calorimetric method. The total hemispherical emittance ε_h is determined by equating electric heat input to the sample with radiative heat loss from the sample to the surroundings. Figure 2 shows the typical experimental setup. The sample is suspended by lead wires and thermocouples inside an evacuated test chamber, the wall of which is coated with a near-black material. The test chamber walls are cooled to low temperature, while the sample is heated electrically through a sheet heater. Temperatures of sample and test chamber wall are monitored by thermocouples. It is assumed that ε_h of the sample is equal to total hemispherical absorbance α_h of its own. When the sample temperature T_S is in a steady state, then the equation of energy balance can be expressed as follows.

$$Q = \varepsilon_h(T_S)\sigma A_S\left(T_S^4 - T_W^4\right) + Q_W + Q_g - Q_r \quad (1)$$

Where σ is the Stefan-Boltzmann constant, Q is the supplied electrical power determined by the electric current and the terminal voltage of the sample, Q_g is a heat loss through residual gas, and Q_r is heat input by inter reflection between sample and test chamber wall. In the present measurement, since the test chamber is kept in high vacuum, and since the surface area of the test chamber is much larger than the total surface area of sample A_S, Q_g and Q_r are neglected. Therefore ε_h is calculated as follows.

$$\varepsilon_h(T_S) = \frac{Q - Q_W}{\sigma A_S\left(T_S^4 - T_W^4\right)} \quad (2)$$

Thus, ε_h of the sample is determined by measuring the supplied electrical power Q, the temperature of sample T_S and test chamber wall T_W, the total surface area of sample A_S, and estimating the heat loss of the sample through lead wires Q_W.

3.2. Experimental apparatus [7]

Figure 3 schematically shows the present experimental apparatus. This system consists of a liquid nitrogen (LN_2) cryostat with a test chamber, a port for sample exchange, a system for an up-and-down motion of a sample, a vacuum system, measuring instruments, and a personal computer, which controls sample temperature and logs the experimental data. The spherical test chamber, inside diameter of which is 250mm, is located at the bottom of the liquid nitrogen cryostat, whose diameter is 510mm and depth is 1400mm. The wall of the test chamber is cooled to 77 K by LN_2 and the inner surface of it is painted by a near-black paint (CHEMGLAZE Z306™), which has very high total hemispherical absorptance. During the measurement, the test chamber is kept under 10^{-5}Pa by using a turbo molecular pump. This is why Q_g is neglected in the present measurement.

3.3. Sample structure

Sample structure is shown in Fig.4. Test samples are made by using two pieces of aluminum plates (20×20×0.5mm) and sandwiched sheet heater. Thermal control films are stuck on the sample plates with heat-resistant glue (KE3417™ or KE3418™, Shin-Etsu Chemical Co., Ltd). The temperature of the sample is measured by a calibrated chromel-almel thermocouple (50μm in diameter), which is attached to the center of the sample with the sheet heater. In order that the distribution of the surface temperature is equal, the sheet heater (19×19mm), which has such a pattern of an aluminum-heating element (240±5Ω) as shown in Fig.4, is adopted in the present measurement. Constantan lead wires (50μm in diameter) in the temperature range from 173 to 373 K and copper lead wires (100μm in diameter) in the temperature range 373 to 700 K are adopted respectively and attached together with the sheet heater with silver paste (Pyro-Duct 597™, Aremko Procucts, Inc.).

4. CALCULATION METHOD [8,9]

Thermal control films usually are thin polymer films with vapor-deposited metal on the back surface as shown in Fig. 5. And it is possible to produce thermal control films with the required values of ε_h by selecting materials (polymer films and vapor-deposited metal) and the appropriate thickness for each layer. The present calculation method for the sample temperature dependence of ε_h enables us to design suitable thermal control films which satisfy the target values of ε_h and to predict the values in the temperature region in which it is difficult to measure experimentally.

This calculation method is performed according to the following procedures, using data for the optical constants of polyimide films and aluminum [10]. And in the present calculation, it is assumed that each layer is homogeneous, no scattering material and has a smooth surface, no temperature dependence of their optical constants.

At first, the optical constants of polyimide films are obtained from a measurement of their normal spectral reflectance and transmittance as the optical constants of UPILEX-S film are shown in Fig. 6. The normal spectral reflectance and transmittance are measured by the Fourier transform spectrometer (Bio-Rad FTS-60A/896) in the wavelength region from 0.25 to 100μm.

Amplitude reflectances of thermal control films are calculated from the optical constants of polyimide films and aluminum, and then the spectral reflectance is calculated with amplitude reflectances. The calculation is made for two cases: with and without considering an interference phenomenon. In the wavelength region from 2.5 to 20μm, in which the interference phenomena of polyimide films are strong, they are considered in calculating an amplitude reflectance and a spectral reflectance.

When an interference phenomenon is not considered, amplitude reflectances accounted for multiplex reflectance at the boundary surface between the *m*-th and (*m*+1)-th layers from the bottom as expressed by

$$R_m^{'}(\lambda,\theta)=r_m+\frac{(1-r_m)^2 R_{m-1}^{'}(\lambda,\theta)\exp(-2\gamma_m d_m)}{1-r_m R_{m-1}^{'}(\lambda,\theta)\exp(-2\gamma_m d_m)} \tag{3}$$

where $\gamma_m = 4\pi k_m/\lambda\cos\theta_m$, $r_m = \left(|r_{Sm}|^2+|r_{Pm}|^2\right)/2$, r_{Sm} and r_{Pm} are the Fresnel coefficients, k_m is the extinction coefficient of the *m*-th layer, θ_m is the incident angle of electromagnetic waves of the *m*-th layer, and d_m is the thickness of the *m*-th layer. Thus, the spectral reflectance of the surface of the thermal control film as a function of the incident angle and the wavelength is expressed by as follows.

$$R(\lambda,\theta)=r_{ma}+\frac{(1-r_{ma})^2 R_{ma-1}^{'}(\lambda,\theta)\exp(-2\gamma_{ma} d_{ma})}{1-r_{ma} R_{ma-1}^{'}(\lambda,\theta)\exp(-2\gamma_{ma} d_{ma})} \tag{4}$$

Where the subscript *ma* indicates the layer number.

On the other hand, when an interference phenomenon is considered, amplitude reflectances which take into account for multiplex reflectance at the boundary surface between the *m*-th and the (*m*+1)-th layers from the bottom are expressed by

$$R''_m(\lambda,\theta) = \frac{r_m + R''_{m-1}(\lambda,\theta)\exp(-i\eta_m)}{1 + r_m R''_{m-1}(\lambda,\theta)\exp(-i\eta_m)} \tag{5}$$

where $\eta_m = 4\pi\hat{n}_m d_m \cos\theta_m / \lambda$, and $\hat{n}_m$ is the complex refractive index of the *m*-th layer. Thus, the spectral reflectance of the surface of the thermal control film as a function of the incident angle and the wavelength is expressed by as follows.

$$R(\lambda,\theta) = \frac{\left|R''_{Sma}(\lambda,\theta)\right|^2 + \left|R''_{Pma}(\lambda,\theta)\right|^2}{2} \tag{6}$$

Where $R''_{Sma}(\lambda,\theta)$ and $R''_{Pma}(\lambda,\theta)$ are the spectral reflectance of S-polarization and P-polarization of the surface of the thermal control film from Eq. (5), respectively. In this way, the spectral reflectance $R(\lambda,\theta)$ of the surface of the thermal control film is obtained by using Eqs. (4) or (6).

Finally, a temperature dependence of ε_h is calculated by integration of the spectral reflectance in the wavelength region from 0.25 to 100μm and in the incident angle of electromagnetic waves from 0 to $\pi/2$, expressed by as follows.

$$\varepsilon_h = \frac{\int_0^{\pi/2}\int_{0.25}^{100}\{1 - R(\lambda,\theta)\} i_b(\lambda,T)\cos\theta\sin\theta\, d\lambda\, d\theta}{\int_0^{\pi/2}\int_{0.25}^{100} i_b(\lambda,T)\cos\theta\sin\theta\, d\lambda\, d\theta} \tag{7}$$

Where *T* is the sample temperature and $i_b(\lambda,T)$ is the Planck's spectral distribution of emissive power. It is possible to ignore the difference between the calculated result and the theoretical value over a restricted wavelength region, as about 97.9% of the emissive power of the blackbody is contained at 173.15 K, and approximately 100.0% at 700 K in this wavelength region. And in Eq. (9), Lambert's cosine law is used in order to convert the normal emissive power into the directional emissive power.

5. RESULTS AND DISCUSSION

In the present experimental measurement of ε_h in the temperature range from 173.15 to 523.15 K, the main factors of the uncertainty are thought as follows: variations of the supplied electrical power Q, measurements of the surface area of specimens A_S, and temperature measurements T_S, T_W. The terminal voltage and the electric current, which determine the supplied electrical power, are measured by a digital multimeter with an accuracy of ±0.11%. The estimated uncertainty of the surface area of specimen is within ±1.0%. And the uncertainty of the temperature measurements is estimated to be within ±0.32 K in the temperature range. Therefore, the overall uncertainty of the present experimental measurements of ε_h is estimated to be at most ±1.5% in the temperature range. As for in the temperature range from 523.15 to 700 K, the uncertainty of the temperature measurements is estimated to be within ±0.62 K. The heat loss of the sample through lead wires Q_W is not considered in calculating ε_h according to Eq. (2). This contributes less than 3% to the uncertainty of ε_h, which is estimated by the heat-conduction equation. The uncertainties of measurements of the supplied electrical power and the surface area of specimen are the same as mentioned above. Consequently, the overall uncertainty of the present experimental measurement of ε_h is estimated to be at most +1.5% and –3.5% in the temperature range 523.15 to 700 K.

The accuracy of the present calculated results is believed to be due mainly to the uncertainty in the optical constants and the thickness of polyimide films. The uncertainty in the optical constants is estimated to be less than ±5%, which corresponds to the experimental results for the spectral reflectance and transmittance of polyimide films. The uncertainty of the thickness of polyimide films is estimated to be less than ±5%. In consequence, the overall uncertainty of the present calculated results of ε_h is within +3.5% and −5.0%.

Figure 7 shows comparisons of the experimental and calculated results for the temperature dependence of ε_h for aluminum-deposited UPILEX-S films (20μm) and aluminum-deposited UPILEX-R films (25μm) and aluminum-deposited Kapton-H films (25μm), respectively.

As for the ε_h of aluminum-deposited UPILEX-S films at low temperatures and aluminum-deposited UPILEX-R films at high temperature, the maximum difference between experimental and calculated results is 0.05~0.07. It is because the calculated optical constants of polyimide films are not correctly obtained, owing to different orientations of polyimide films between sample specimens. At the other temperature region, however, the calculated results agree very well with the experimental results on the whole. According to these agreements, it has been proved that this present calculation method is an effective means to predict the temperature dependence of ε_h in the temperature range from 173.15 to 700 K.

Owing to this experimental measurements and calculation in the temperature range from 173.15 to 700 K, it has been observed that the temperature dependence of ε_h of thermal control films is remarkable and the values have a maximum around 410 K. The reason why the values have a maximum around 410 K can be thought as follows. It is because the thermal control film has a low reflectance, that is a high absorptance, at the wavelength region from 6 to 10μm, which agrees the wavelength at which the emissive power from a blackbody at around 410 K is a maximum as shown in Fig.8.

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Table I. Thermal Environment Around Mercury Orbit [1,2]

	Mercury	Earth	Notes
Solar Intensity	6220~14330 $W \cdot m^{-2}$	1289~1421 $W \cdot m^{-2}$	4.6~10.6 times
Albedo (Intensity)	0.06 (373~716 $W \cdot m^{-2}$)	0.25~0.35 (322~497 $W \cdot m^{-2}$)	
Radiative Intensity	5847~13470 $W \cdot m^{-2}$	216~258 $W \cdot m^{-2}$	*

*Peak value at right insolation is shown for Mercury, while the averaged value for Earth.

Table II. Properties of Polyimide Films [5,6]

	Density ($g \cdot cm^{-3}$)	T_g	T_{20000}
UPILEX-S	1.47	632 K	563 K
UPILEX-R	1.39	576 K	543 K
Kapton-H	1.42	700 K	538 K

FIGURE CAPTONS

Fig.1. Chemical structure of polyimide films.

Fig.2. Principle of the measurement.

Fig.3. Schematic drawing of experimental apparatus.

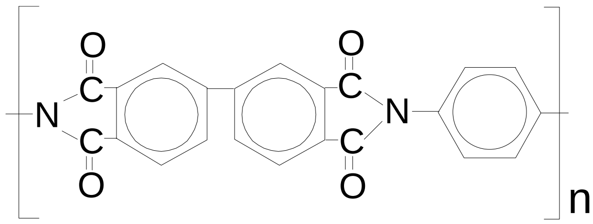
Fig.4. Sample structure.

Fig.5. Calculation model for thermal control films.

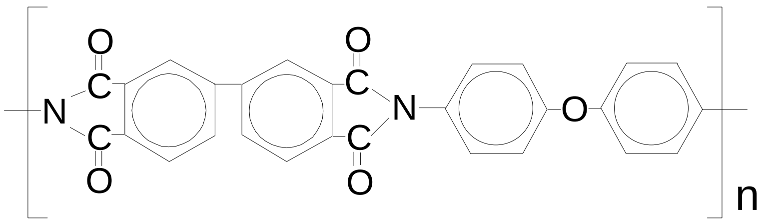
Fig.6. Optical constants of UPILEX-S.

Fig.7. Total hemispherical emittance of thermal control films.

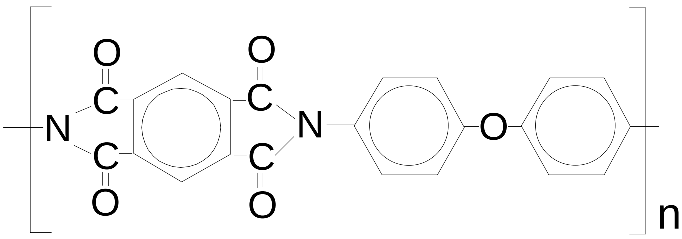
Fig.8. Spectral reflectance of thermal control films.



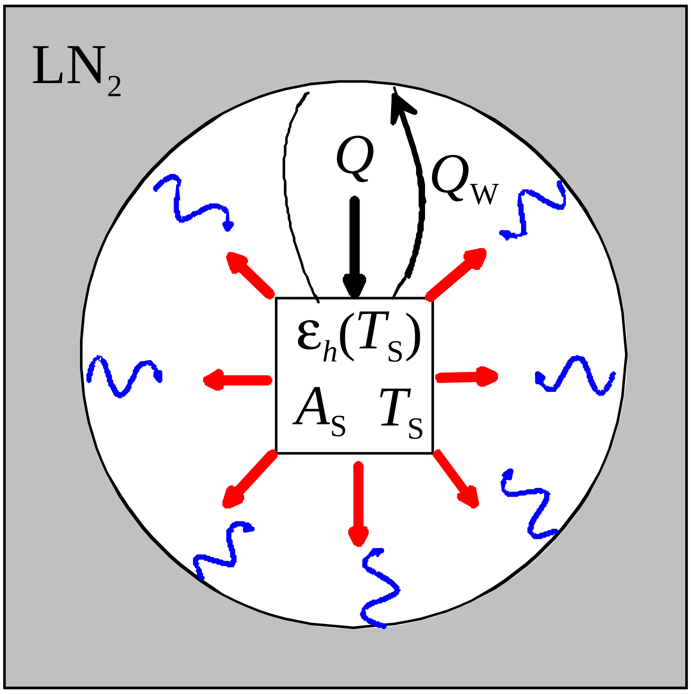
UPILEX-S



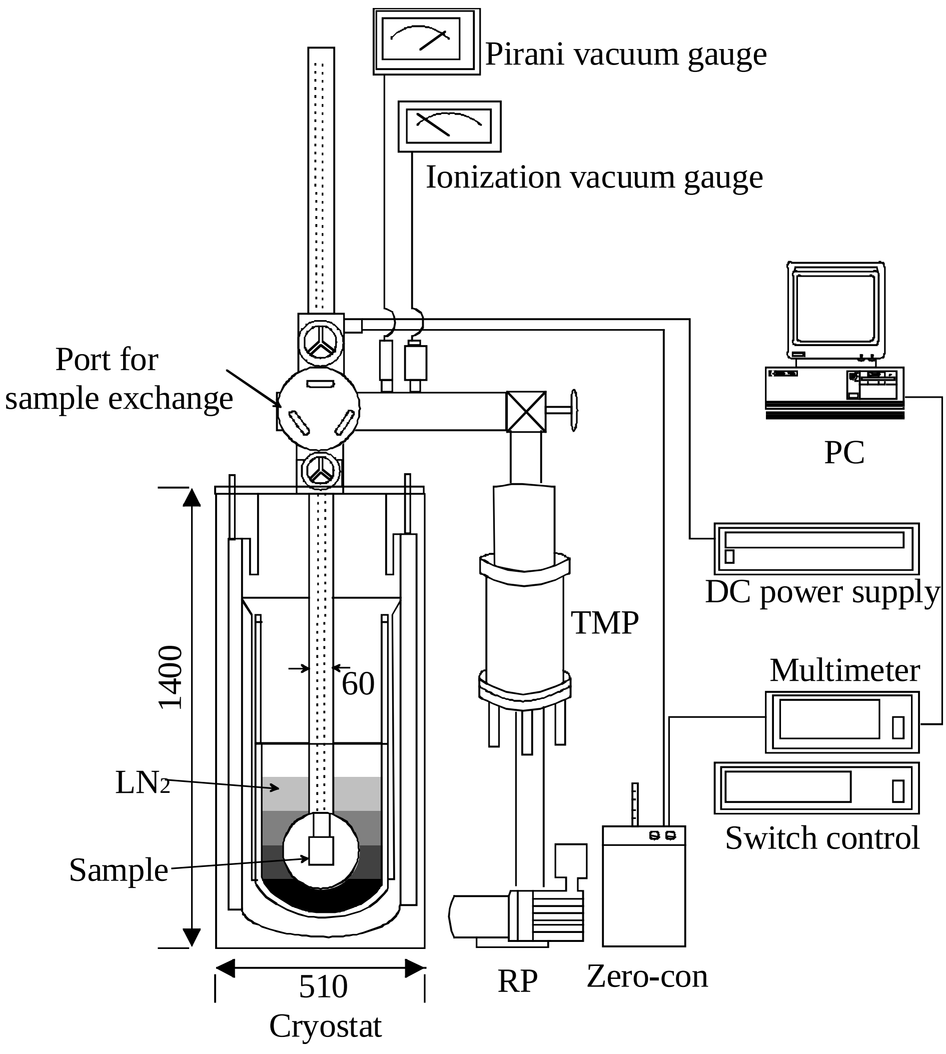
UPILEX-R

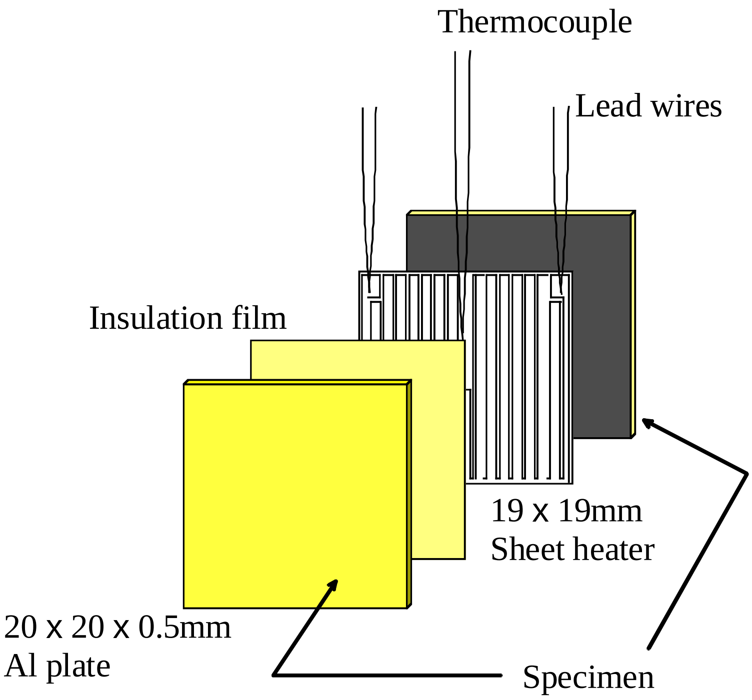


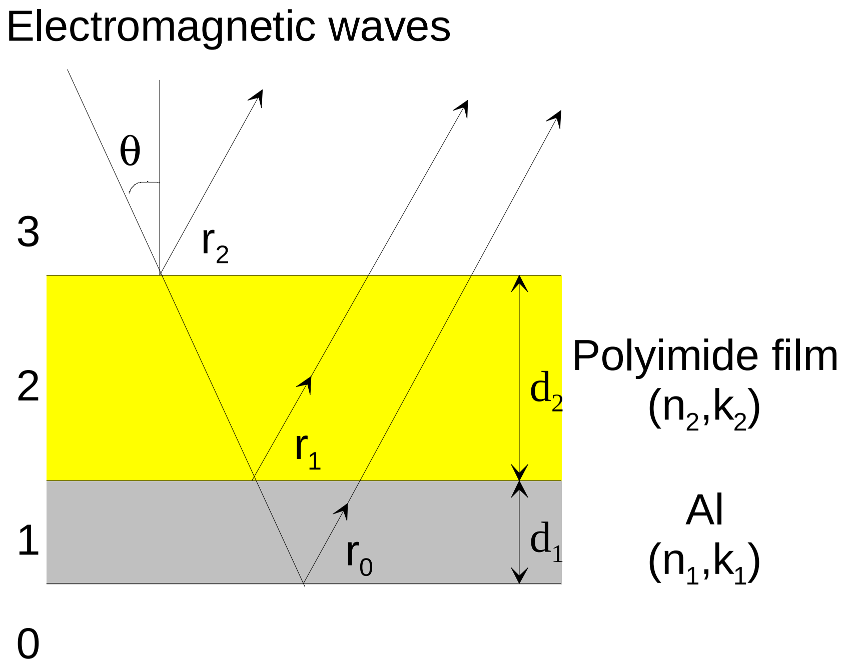
Kapton-H



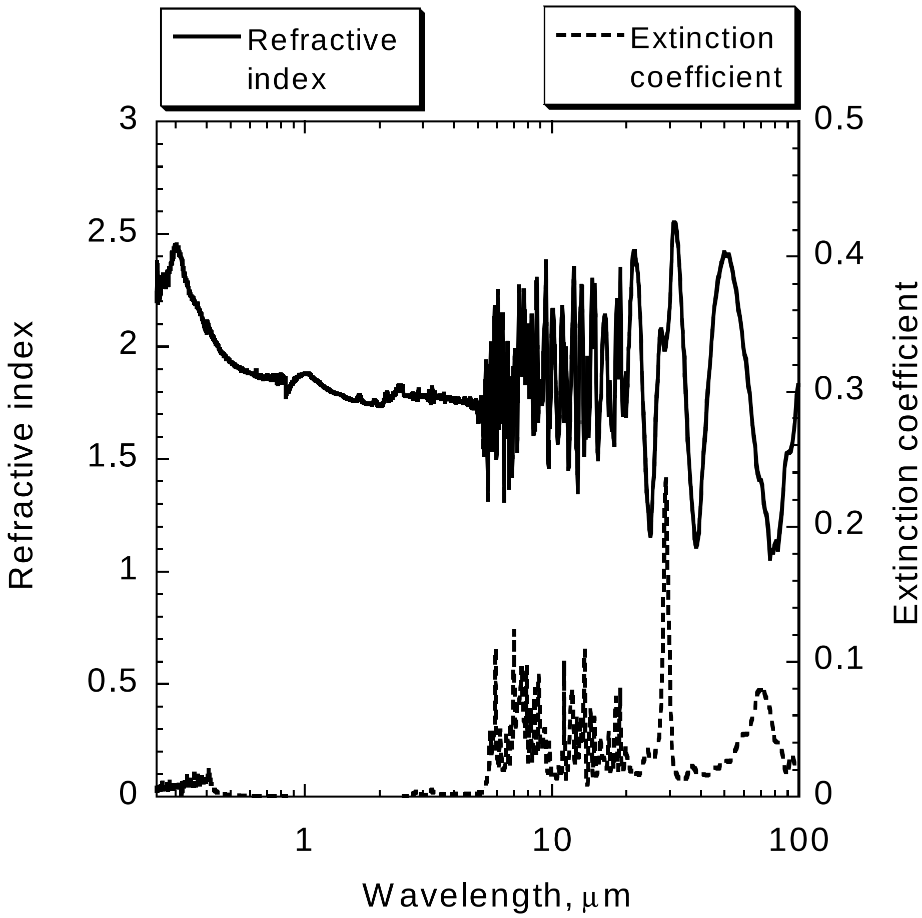
LN2
Q
QW
εh(TS)
AS TS


Pirani vacuum gauge
Ionization vacuum gauge
Port for
sample exchange
PC
DC power supply
TMP
Multimeter
60
1400
LN2
Sample
Switch control
RP
Zero-con
510
Cryostat

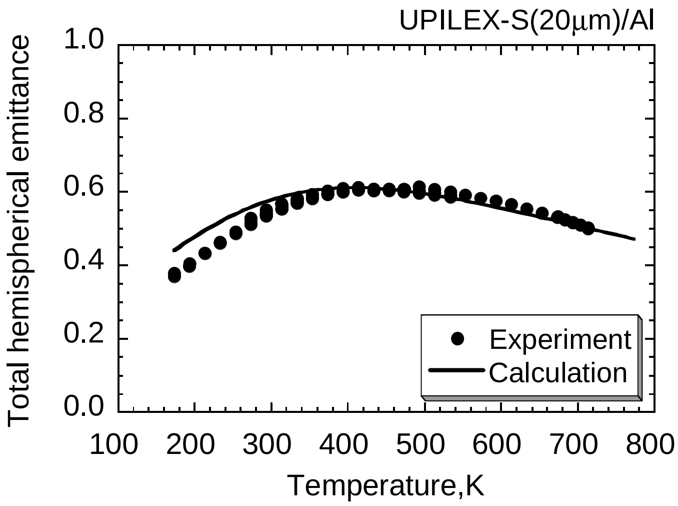

Thermocouple
Lead wires
Insulation film
19 x 19mm
Sheet heater
20 x 20 x 0.5mm
Al plate
Specimen

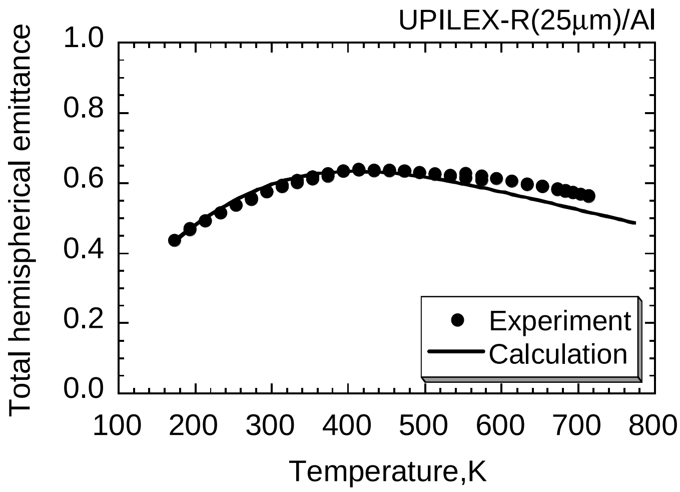


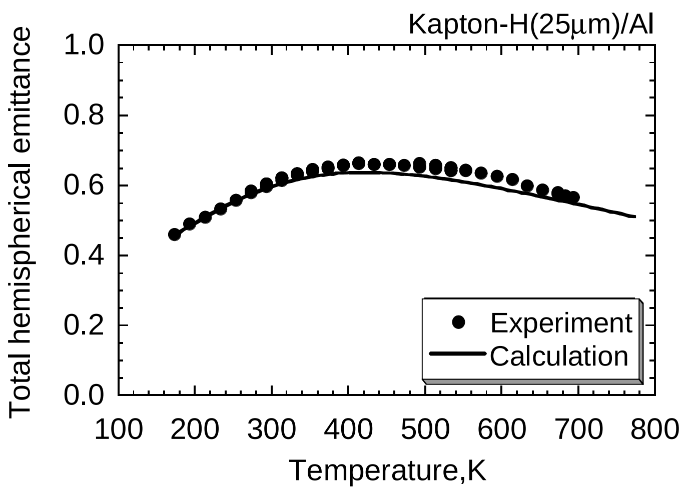
Electromagnetic waves
θ
3
r_2
2
d_2
Polyimide film
(n_2,k_2)
r_1
1
d_1
Al
(n_1,k_1)
r_0
0

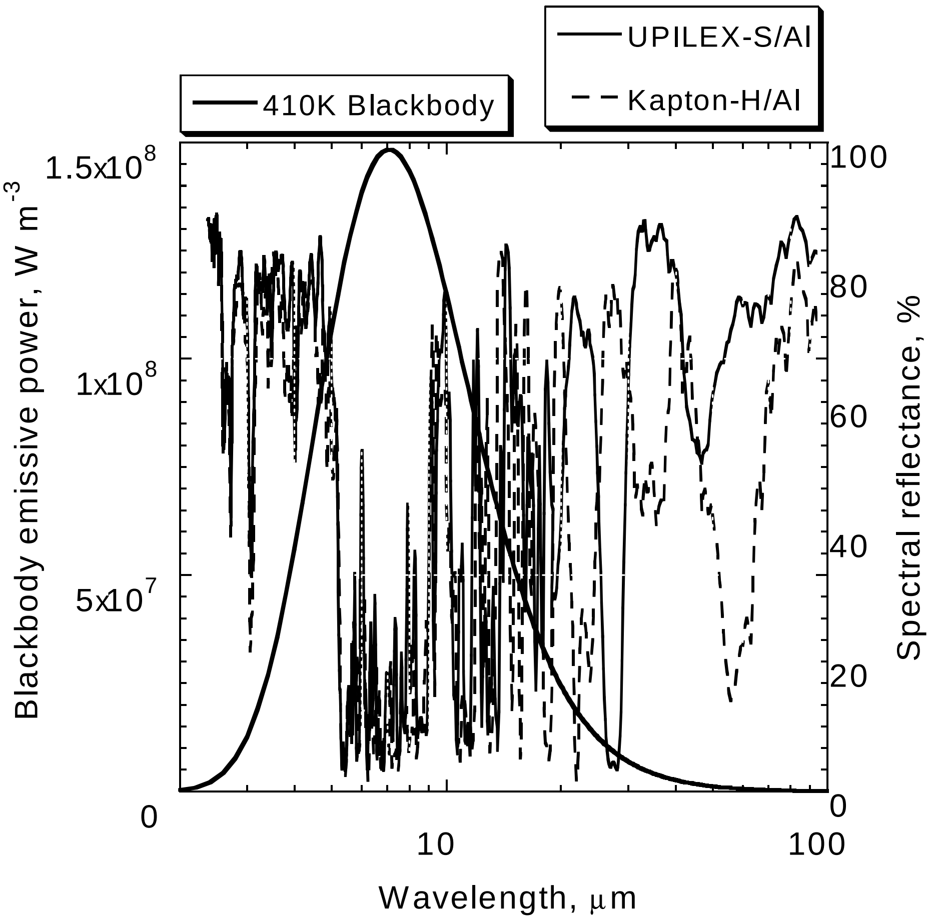


Refractive index
Extinction coefficient
3
2.5
2
1.5
1
0.5
0
0.5
0.4
0.3
0.2
0.1
0
1
10
100
Wavelength, μm
Refractive index
Extinction coefficient


UPILEX-S(20μm)/Al
Total hemispherical emittance
1.0
0.8
0.6
0.4
0.2
0.0
100
200
300
400
500
600
700
800
Temperature,K
Experiment
Calculation


UPILEX-R(25μm)/Al
Total hemispherical emittance
1.0
0.8
0.6
0.4
0.2
0.0
100
200
300
400
500
600
700
800
Temperature,K
Experiment
Calculation


Kapton-H(25μm)/Al
Total hemispherical emittance
1.0
0.8
0.6
0.4
0.2
0.0
100
200
300
400
500
600
700
800
Temperature,K
Experiment
Calculation



UPILEX-S/Al
Kapton-H/Al
410K Blackbody
1.5x10^8
1x10^8
5x10^7
0
Blackbody emissive power, W m^-3
100
80
60
40
20
0
Spectral reflectance, %
10
100
Wavelength, μm